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Original Article

High self-perceived exercise exertion before bedtime is associated with greater objectively assessed sleep efficiency

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ABSTRACT

Objective: To assess the association between self-perceived exercise exertion before bedtime and objectively measured sleep.
Methods: Fifty-two regularly exercising young adults (mean age, 19.70 years; 54% females) underwent sleep electroencephalographic recordings 1.5 h after completing moderate to vigorous exercise in the evening. Before sleeping, participants answered questions regarding degree of exertion of the exercise undertaken.
Results: Greater self-perceived exertion before bedtime was associated with higher objectively assessed sleep efficiency ($r = 0.69$, $P < 0.001$); self-perceived exertion explained 48% of the variance in sleep efficiency ($R^2 = 0.48$). Moreover, high self-perceived exercise exertion was associated with more deep sleep, shortened sleep onset time, fewer awakenings after sleep onset, and shorter wake duration after sleep onset. Multiple linear regression analysis showed that objective sleep efficiency was predicted by increased exercise exertion, shortened sleep onset time, increased deep sleep, and decreased light sleep.
Conclusion: Against expectations and general recommendations for sleep hygiene, high self-perceived exercise exertion before bedtime was associated with better sleep patterns in a sample of healthy young adults. Further studies should also focus on elderly adults and adults suffering from insomnia.

1. Introduction

A broad variety of studies has found a positive association between regular exercising and physical and psychological health. For example, Gerber et al. [1] showed that greater cardiorespiratory fitness protected against stress-related symptoms of burnout and depression. Likewise, Lindwall et al. [2] found in a large sample of middle-aged adults ($n = 3717$; mean age, 46.9 years) that physical exercise measured at baseline predicted reduced symptoms of depression, anxiety, and burnout 6 years later. Similarly, numerous cross-sectional, longitudinal, and interventional studies have confirmed the positive effect of physical activity on sleep. For instance, Kalak et al. [3] showed that regular running in the morning for three consecutive weeks improved sleep as objectively assessed in healthy adolescents compared with controls. Lang et al. [4], again sampling adolescents, showed that increased physical activity, whether assessed subjectively or objectively, predicted both subjective and objective improved sleep. As for adults, Loprinzi and Cardinal [5] found associations between favorable sleep and physical activity. Likewise, de Castro Toledo Guimaraes et al. [6] reported higher self-reported sleep patterns in elderly physically active women, compared with their sedentary counterparts. Focusing on adults suffering from insomnia, Passos et al. [7] assessed 19 patients aged 45 years suffering from primary insomnia, showing that a 6-month exercising intervention (3 days/week of 50 continuous minutes on the treadmill) led to significant improvements in objective sleep and subjective quality of life. Similarly, Reid et al. [8] assessed 17 subjects aged 61 years suffering from insomnia, and after a 16-week exercise intervention an increase in subjective sleep, mood and vitality was reported.

A major reason why adults do not exercise as much as they would wish is lack of time [9]. On the other hand, evenings and especially the period after work and family time would seem ideal for exercising, though both the scientific community and lay opinion strongly discourage vigorous exercise in the run up to bedtime [10–12]. However, and surprisingly, there is little reliable scientific evidence to support this recommendation. Evidence from experimental studies has failed to show that regular evening exercise

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adversely affects sleep [13–15]. Likewise, epidemiological studies have not shown evening exercise to be associated with impaired sleep [16,17]. Most importantly, Buman et al. [14] reported data on 1000 adults aged 23–60 years from the 2013 National Sleep Foundation Sleep in America Poll. The main results were that evening moderate-to-vigorous exercisers did not differ in any of the self-reported sleep variables compared with non-exercisers. More specifically, whereas morning vigorous exercisers reported more favorable sleep pattern (i.e. higher sleep quality; waking up refreshed), most individuals performing vigorous evening exercise ≤4 h before going to bed indicated that their sleep was of equal or of higher sleep quality and duration on days they exercised, compared with days they did not exercise. In effect, neither surveys nor experimental studies have found any negative influence of evening exercise upon sleep. Accordingly, it is somewhat puzzling that sleep hygiene recommendations discourage evening exercise prior to sleep.

Is increased exercise exertion associated with specific changes in objective sleep architecture and sleep continuity? To the best of our knowledge, only one intervention study and one cross-sectional study have examined these connections. Dworak et al. [18] assessed 11 healthy children (mean age: 12.6 years) during two bicycle ergometer sessions 3–4 h prior to sleep. One session involved exercise exertion at 65–70% of maximum heart rate (moderate exercise condition); the other session involved exercise exertion at between 85% and 90% and exhaustion of maximum heart rate (vigorous exercise condition). After each session, sleep electroencephalograms (EEGs) were performed, and sleep-EEGs of the two nights were compared. Compared with the moderate exercise condition, the vigorous exercise condition led to increased slow wave sleep and decreased stage 2 sleep. Effectively, Dworak et al. [18] found a dose–response relationship between exercise exertion and change in sleep architecture. Similarly, Brand et al. [19] found among a sample of 38 adolescents (mean age, 18.6 years) a dose–response association between increasing weekly moderate physical activity on the one hand and increasing slow wave sleep and decreasing rapid eye movement (REM) sleep on the other. Additionally, linear regression analyses showed that weekly exercise duration predicted shortened sleep onset latency, fewer awakenings, and increased slow wave sleep. These two studies indicate an association between increasing exercise exertion (whether assessed cross-sectionally or produced via an intervention) and a shift towards increased deep sleep. On the other hand, given that in neither study was participants' sleep assessed immediately following exercising, it remains unclear to what extent an acute bout of exercise might influence sleep directly afterwards.

The aims of the present study were therefore to test three hypotheses. First, following the recommendation of the American Sleep Association [10], we anticipated that intense exercise before bedtime would have a negative impact on sleep. Second, following Dworak et al. [18] and Brand et al. [19], we expected more slow wave sleep and reduced light sleep and REM sleep with increasing exercise exertion. Third, we assumed that objective sleep efficiency would be predicted by shortened sleep onset time, increased deep sleep and decreased light sleep, but not by exercise exertion. Next, we treated as exploratory the question of up to what extent exercise exertion might be associated with mood, tiredness, and feeling hungry (both following exercise in the evening and in the morning after).

To test the hypotheses and address the exploratory question, a sample of physically and psychologically healthy and regularly exercising young adults was assessed with respect to self-perceived degree of exertion in their exercise and sleep as assessed via sleep-EEG devices.

We believe that the present study has the potential to shed light on the issue of whether evening exercise should be discouraged. The findings may also have practical implications, since, for most employed adults and parents, evening hours often provide the only opportunity for exercise.

2. Methods

2.1. Sample

A total of 52 young adults [age (mean ± standard deviation), 19.70 ± 0.30 years] took part in the study. Of these, 28 were female (19.56 ± 0.15 years), and 24 were male [19.35 ± 0.31 years; $t(50) = 0.86$, $P = 0.89$]. Female (21.32 ± 3.34 years) and male (20.01 ± 4.53 years) participants did not differ in body mass index (BMI) [$t(50) = 1.01$, $P = 0.66$].

2.2. Procedure

Participants were recruited from a high school in the Canton of Basel-Land, a district of the German-speaking North Western part of Switzerland.

All eligible students were informed of the purpose of the study and the voluntary basis of their participation. All participants were assured of the confidentiality of their responses and gave informed consent. Of the 60 students approached, three (5%) had to be excluded due to unexpected illness; data from two participants (3.3%) had to be excluded due to technical problems related to sleep-EEG recordings, and three participants (5%) completed the questionnaires, but withdrew from sleep-EEG registration. Thus, complete data were available from 52 students (86.7% of the sample approached). A psychiatric interview (Mini International Neuropsychiatric Interview [20]) ensured that only participants without psychiatric disorders (e.g. affective disorders, eating disorders, substance abuse disorders, sleep disorders, or others) were enrolled in the study. Most importantly, eligible participants had to report no current or past sleep difficulties within the last 6 months. Additionally, a medical doctor asked eligible participants about current or past (last 6 months) physical illnesses such as flu, inflammations, or severe somatic diseases. Finally, participants were asked to refrain from intake of psychoactive and sleep-altering substances (alcohol, cannabis, amphetamines, modafinil, nicotine, medicaments; mood- or energy-enhancing drinks) for 2 weeks prior to the sleep-EEG registration. Moreover, a key inclusion criterion was that a participant was regularly doing sports two or three times a week in the evening for at least 70 consecutive minutes during the previous two school terms (12 months). This was to ensure that only individuals undertaking regular moderate-to-vigorous exercise were enrolled in the study; we wished to exclude the participation of mere beginners, since possible associations between exercise intensity and sleep could have been confounded by their inclusion.

The study was performed during a normal school term. All eligible participants were expected to be performing normal daytime activities during weekdays such as attending regular school schedules without taking days off or holidays or doing shift work. Moreover, they were expected to continue their regular exercise routines two or three times a week in the evening. Additionally, there were no changes of school, family structure, or any other event, which might have significantly influenced participation. The study was approved by the local ethics committee and performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

2.3. Instruments

2.3.1. Sleep-EEG recordings

The sleep-EEG device was applied twice. For the first application, participants were asked to sleep with the sleep-EEG device,

in order to exclude possible 'first night effects'. No registration was performed on this application. The consecutive night, sleep registration was performed.

On the day of the recording night, participants had to attend regular school schedules and their regular sports activities; the sleep registration was performed during a weeknight following a day with exercise, and with a regular school day the morning after; in other words, the recording night was a regular weeknight in respect of school schedule that day and the following day. Furthermore, participants were requested to adhere to their normal evening routines, that is to say, to go to bed at their usual time, which was between 21:00 and 22.30 and to get up between 06:00 and 07:30.

Regular sports activity lasted for 65–90 min and ended between 20:45 and 21:15. Afterwards, following the advice of O'Connor and Cook [21], sleep-EEG recordings were commenced at the latest 70 min after completing the sports activity. Sleep-EEG recordings were performed at home using a three-channel EEG device (C3–A2, C4–A1, Fp2–A1; electro-oculogram; electromyogram; Somnowatch®, Randersacker, Germany). Sleep polygraphs were visually analyzed by two experienced raters according to standard procedures [22]. Sleep-EEG recordings of 20 participants (38.6%) were independently rated by the two raters, with high inter-rater agreement (kappa = 0.89). Sleep parameters were analyzed according to the definitions in the standard program described by Lauer et al. [23]. The device was applied by a laboratory technician. The device enables assessment of total sleep time (TST), sleep period time (SPT), sleep onset latency (SOL), sleep efficiency (SE), stages 1–4, light sleep (stages 1 and 2), slow wave sleep (stages 3 and 4), REM sleep, REM sleep latency, and number and time of awakenings after sleep onset.

2.3.2. *Assessing self-perceived exercise exertion and sleep-related items*

To assess self-perceived degree of exertion, in the absence of standardized tools, a self-administered questionnaire was constructed. The questionnaire was completed when the participant was already in bed and ready to sleep. It consisted of four items: "During the sport session, were you short of breath?" (five-point Likert scale: 0, not at all; 20, a bit; 50, regularly; 80, often; 100, always); "During the sport session, were you sweating?" (five-point Likert scale: 0, not at all; 20, a bit; 50, regularly; 80, often; 100, always); "During the sport session, did you have a high pulse rate?" (five-point Likert scale: 0, not at all; 20, a bit; 50, regularly; 80, often; 100, always). Higher scores reflected greater the self-perceived exercise exertion. Next: "The exercise exertion was at *x*% of your maximum performance." A mean score was calculated for the four items, with higher means indicating greater exercise exertion.

In the evening, additional items, in each case with an eight-point Likert response scale, asked about current mood (1, very bad mood; 8, very good mood), tiredness (1, very awake; 8, very tired), and feeling hungry (1, not at all hungry; 8, very hungry) when in bed and ready to sleep. In the morning, items asked about current mood (1, very bad mood; 8, very good mood), tiredness (1, very awake; 8, very tired), feeling hungry (1, not at all hungry; 8, very hungry), and subjective sleep quality (1, very poor sleep quality; 8, very high sleep quality).

2.3.3. *Statistical analysis*

A series of Pearson's correlations was performed between exercise exertion, mood, tiredness, feeling hungry, and objective sleep data. Next, to predict objective sleep efficiency, a linear regression analysis (stepwise exclusion) was performed with objective sleep efficiency as dependent variable and age, gender, BMI, exercise exertion, and variables of sleep continuity and sleep architecture as possible predictors. Statistical computations were performed with SPSS® 20.0 (IBM Corp., Inc., Armonk, NY, USA) for Apple MacIntosh®.

Table 1
Descriptive statistics and correlation coefficients between exercise exertion and objective sleep variables ($N = 52$).

	Exercise exertion (r)	Descriptive statistics mean (SD)
Sleep efficiency (%)	0.71***	94.20 (1.98)
SOL (min)	−0.33*	10.02 (5.31)
SPT (min)	−0.39**	409.65 (12.94)
WASO (no.)	−0.66***	2.59 (2.52)
WASO (duration, min)	−0.42**	8.32 (9.65)
REM duration	−0.38**	73.96 (19.83)
S1 (min)	−0.26	12.60 (2.45)
S2 (min)	−0.42**	154.23 (30.12)
S3 (min)	0.68***	55.64 (13.69)
S4 (min)	0.15	97.65 (14.97)
Light sleep (min)	−0.39**	166.46 (29.33)
Deep sleep (min)	0.34**	152.06 (23.46)
Descriptive statistics (%), mean (SD)	75.26 (15.92)	

SOL, sleep onset latency; SPT, sleep period time; WASO, wakenings after sleep onset; REM, rapid eye movement sleep; S, stage.
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

3. Results

3.1. *Correlations between exercise exertion and objective sleep parameters*

Table 1 gives the descriptive statistics and correlation coefficients between exercise exertion and objective sleep variables.

Greater exercise exertion was associated with higher sleep efficiency, shortened sleep onset latency, fewer awakenings and shorter duration of awakenings after sleep onset, less light sleep and more deep sleep.

3.2. *Correlations between exercise exertion and sleep-related variables*

Table 2 shows the descriptive statistics and correlation coefficients between exercise exertion and sleep-related variables. Greater exercise exertion was associated with increased tiredness and better mood, and with decreased feelings of hunger in the evening. Greater exercise exertion the previous evening was associated with increased tiredness, better mood, and, descriptively, with better sleep quality, along with decreased feelings of hunger the following morning.

3.3. *Predicting objective sleep efficiency*

To predict objective sleep efficiency, a multiple linear regression analysis (stepwise exclusion) was performed with objective sleep efficiency as dependent variable and age, gender, BMI, exercise exertion, and variables of sleep continuity and sleep architecture as

Table 2
Descriptive statistics and correlation coefficients between exercise exertion and sleep-related variables ($N = 52$).

	Exercise exertion (r)	Descriptive statistics mean (SD)
Tiredness when going to bed	0.58***	6.29 (1.85)
Feeling hungry when going to bed	−0.39**	4.28 (1.81)
Mood, evening	0.38**	5.78 (2.12)
Mood, morning	0.32*	5.06 (1.28)
Tiredness, morning	0.31*	5.76 (2.17)
Feeling hungry, morning	−0.62***	3.35 (1.76)
Sleep quality	0.29	4.24 (1.08)
Descriptive statistics (%), mean (SD)	75.26 (15.92)	

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Table 3
Multiple linear regression models to describe the influence of exercise exertion, and sleep continuity and sleep architecture variables on objective sleep efficiency.

Variables	Coefficient	Standard error	Coefficient (β)	95% CI	t	P	R	R^2	Durbin–Watson statistics
Intercept	93.32	0.896	–	91.51 to 95.13	104.11	0.000	0.69	0.48	1.99
Exercise exertion	0.001	0.001	0.35	0.002 to 0.003	9.75	0.000			
SOL	0.093	0.015	−0.55	−0.483 to −0.035	−13.76	0.000			
Deep sleep	0.421	0.031	0.51	0.083 to 0.102	19.45	0.000			
Light sleep	−0.092	0.005	−0.22	−0.002 to −0.001	6.64	0.000			
WASO	−0.187	0.035	−0.14	−0.257 to −0.116	−5.33	0.000			

CI, confidence interval; R, multiple correlation coefficient; R^2, multiple coefficient of determination; SOL, sleep onset latency; WASO, wakenings after sleep onset.
Excluded variables: rapid eye movement sleep, age, gender, body mass index.

possible predictors. To do so, first, a series of Kolmogorov–Smirnov tests showed that all variables (except gender) were normally distributed. Second, the Durbin–Watson coefficient was between 1.5 and 2.5, indicating independence of residuals. Third, the multiple linear regression model (R and R^2) sufficiently explained the dependent variable (Table 3).

The objective sleep efficiency was predicted by increased exercise exertion, shortened SOL, increased deep sleep, decreased light sleep, and fewer awakenings after sleep onset, whereas age, gender, BMI, and REM sleep were excluded from the equation.

4. Discussion

The key findings of the present study are that among a sample of healthy young adults, self-perceived exercise exertion was positively associated with objectively measured sleep efficiency, and with shortened SOL, fewer awakenings after sleep onset, along with light sleep and more deep sleep. Objective sleep efficiency was predicted by increased exercise exertion, more deep sleep, less light sleep, fewer awakenings after sleep onset, and shortened SOL. Moreover, with greater self-perceived exercise exertion, tiredness increased, mood was better, and feelings of hunger were lower.

Three hypotheses and an exploratory research question were formulated and each of these is considered now in turn.

Our first hypothesis was that greater exercise exertion one-and-a-half hours before bedtime would be associated with impaired sleep, as expressed by poorer sleep efficiency or, for instance, prolonged SOL. The hypothesis was not supported. On the contrary, greater exercise exertion was associated with better sleep efficiency and, for example, shortened SOL. Therefore, our findings are at odds with both scientific and lay opinion, which discourage vigorous evening exercise prior to bedtime. Rather, the present pattern of results is in accord with those findings from experimental studies showing that sleep was better after evening exercise [13,18,24,25], and from a larger survey [14] showing that evening moderate-to-vigorous exercisers did not differ in any of the self-reported sleep variables compared with non-exercisers. Even more importantly, Buman et al. [14] showed that individuals performing vigorous evening exercise (<4 h before going to sleep) indicated that sleep was of equal or of higher quality and duration on days they exercised, compared with days on which they did not exercise. The present investigation expands therefore those studies unable to show a negative impact of evening exercise on sleep, in that the same direction of association was apparent when assessing sleep objectively, and in that a dose–response relation between exercise exertion and change in sleep continuity and sleep architecture was observed.

Our second hypothesis was that subjectively greater exercise exertion one-and-a-half hours before bedtime would be associated with a shift toward more deep sleep and less light sleep or REM sleep, and this hypothesis was supported. Greater self-perceived exercise exertion was associated not only with less light sleep, more deep sleep, and less REM-sleep, thus confirming the results Dworak et al. [18] reported for a sample of young adolescents, but also with better sleep continuity, as expressed by higher sleep efficiency, shorter SOL, and fewer awakenings after sleep onset. Importantly, the present results accord well with a previous study [19], in which a continuously increasing amount of moderate-to-vigorous exercising during the week was positively associated with more deep sleep and less REM sleep. Moreover, in our opinion, the present evidence is consistent with other findings reported by Brand et al. [26], who observed that despite frequent and vigorous exercise – even in the evening – high-performing athletes reported better subjective sleep efficiency and longer sleep duration than a control group.

Our third hypothesis was that objective sleep efficiency would be predicted by shortened SOL, increased deep sleep, decreased light sleep, and fewer awakenings after sleep onset, but not by exercise exertion, though data did not fully support this assumption, in that against expectations an increased exercise exertion was also an important predictor in the equation. Accordingly, the first hypothesis was further supported.

Next, we treated as exploratory the extent to which self-perceived exercise exertion and mood, tiredness and feelings of hunger might be associated. It turned out that greater exercise exertion one-and-a-half hours before bedtime was associated with better mood and greater tiredness, along with feeling less hungry. These findings merit particular attention. First, there is evidence that exercising has a beneficial effect on mood [27]. For example, Herring et al. [28] and Walter et al. [29] observed anxiolytic and mood-enhancing effects following acute bouts of exercise. Likewise, and most importantly, exercise in the form of regular walking led to substantive improvements and remission in female patients suffering from treatment-resistant major depressive disorders [30]. From a physiological point of view, it appears that regular exercise leads to a broad variety of physiological changes such as an increased secretion of brain-derived neurotrophic factor (BDNF), neurotransmitter release [31], and regional blood flow alterations [32], all of which have a positive influence on mood and anxiety. In these respects, Cotman et al. [33] concluded that exercise improves many aspects of brain function and overall brain health. Following Cotman et al. [33], exercise seems to increase synaptic plasticity by directly affecting synaptic structure and potentiating synaptic strength, where the induction of central and peripheral growth factors and growth factor cascades seems to be key for structural and functional change (see also [34]). This kind of association was observed, for example, by Chaddock-Heyman et al. [35]: the authors found specific neuronal changes and enhanced specific cognitive performance in 9-year-old children following a 9-month physical activity program when compared with controls. Chaddock-Heyman et al. [35] concluded that physical activity during childhood seems to enhance specific elements of prefrontal cortex function involved in cognitive control.

As regards the neurophysiological association between exercising and sleep, we believe the following dynamics are involved.

Exercising increases growth hormones, which are particularly strongly secreted during deep sleep. As higher secretions of growth factor hormones and lower secretions of cortisol, among others, modulate sleep homeostasis [36], it seems likely that exercising leads to higher secretion of growth factors, which in turn enhances deep sleep and reduces REM sleep, a pattern of change in sleep architecture observed in the present study.

Next, we also observed a reduction in feeling hungry following greater exercise exertion, both before and after sleeping. The association between exercising and eating behavior is complex and a more detailed discussion is beyond the scope of the present study though, for example, Martjins et al. [37] argued that short-term appetite control is positively modified by exercise (see Martjins et al. [37] for a thorough discussion).

Despite the intriguing results, several caveats remain. First, the sample consisted of highly selected and physically and psychologically healthy young adult participants who were exercising regularly; therefore, the sample is not representative of adults as a whole. In this regard, second and most importantly, it remains unclear to what extent exercising or greater exercise exertion might positively or negatively impact on the sleep of those who do not exercise at all or who exercise irregularly, beginners, or, for example, those suffering from sleep disturbances. Most importantly, it remains unclear to what extent the present pattern of results might be generalized to older subjects such as postmenopausal women, the largest group of insomniacs. Further studies should therefore focus on older adults and, for instance, postmenopausal women. However, we note that physically active elderly women reported more favorable sleep patterns [6]. Likewise, interventions of physical activity lasting for 16 weeks [8] to 6 months [7] led to increased subjective [8] and objective [7] sleep in elderly people suffering from insomnia. Accordingly, though highly speculative, one may assume that a similar pattern of results of the present study should also be observed in elderly people suffering from insomnia. In these regards, we also note that participants of the present study did not have past problems with sleep and they did not suffer from symptoms of depression and anxiety; that is, the present pattern of results might not be transferred to patients suffering from depressive disorders or other psychiatric disorders. Third, only young people willing and able to participate volunteered in the study; therefore, findings might be biased by motivational or by other psychological factors. In this respect and fourth, the pattern of results might reflect latent but unassessed physiological or psychological factors. More specifically, recent research has shown that higher levels of BDNF are associated with better sleep [38] and increased exercise [39]. Therefore, future studies might assess BDNF as a possible 'missing link' in explaining the association between exercising and sleep. Last, exercising and exercise exertion per se were assessed via self-ratings, and a systematic bias in estimating exercising and exercise exertion cannot be excluded. However, we note that even if participants were biased in their estimations of exertion, such bias would not explain the correlations found with objectively assessed sleep variables. Nonetheless, future research should include objective measurement of physical activity.

5. Conclusions

Among a sample of healthy young adults, self-perceived exercise exertion and objectively assessed sleep were positively associated. The present pattern of results puts into question both scientific and lay opinion that increased exercise exertion in the evening should be avoided immediately prior to bedtime.

Conflicts of interest

None declared.

The ICMJE Uniform Disclosure Form for Potential Conflicts of Interest associated with this article can be viewed by clicking on the following link: http://dx.doi.org/10.1016/j.sleep.2014.05.016.

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